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Role of Public and Private Soybean Breeding Programs in the Development of Soybean Varieties Using Biotechnology

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Modern biotechnology has and will continue to play a valuable role in public and private soybean breeding programs. Tools provided by biotechnology will not replace soybean breeding in the public and private sectors but rather will help provide new discoveries and improve upon the overall efficiency of soybean improvement. Public soybean breeders conduct basic plant breeding research in breeding methodology and germplasm development. In addition, public breeders are involved in educating future plant breeders with the latest biotechnological advances in molecular genetics/biology and laboratory techniques as well as conventional plant breeding practices. The majority of variety development is conducted by private soybean breeders. Biotechnology can be used in virtually every facet of plant breeding activities by both public and private soybean breeders.

Key words: biotechnology, genetically modified organism, soybean breeding.

Introduction

Biotechnology has been practiced by man since plants and animals were first domesticated thousands of years ago. Biotechnology in its most simplistic sense is the genetic modification of living organisms. Hence, all crop varieties grown today, including soybean, have had their DNA manipulated—the essence of biotechnology. More recently, biotechnology implies a deliberate manipulation of the DNA of living organisms, usually through the use of genetic engineering, in which genes are transferred via a vector from one organism to another, bypassing sexual reproduction. The revolution in plant biotechnology is and will be an important contributor to plant breeding programs, including soybean. Plant biotechnology depends upon a number of laboratory procedures that have been developed recently to manipulate DNA and provide new genes of interest to the plant breeder. These procedures have resulted in crop plants that have great commercial value, and many companies are marketing genetically engineered crop varieties. In addition, biotechnology has allowed scientists, as never before, to expand their visions of designing new crop plants to serve humankind.

The first genetically engineered crop variety was the Flavr-Savr™ tomato, engineered for delayed ripening, which was released in 1994 (Sonnewald, 2003). The global area grown to genetically modified (GM) crops increased by 2002 to 145 million acres, which represents more than 5% of the land mass of the United States or China and almost two and one half times the total land mass of the United Kingdom (International Service for the Acquisition of Agri-biotech Applications, 2003). Four countries grew the most GM crops in 2002: The United States had the largest global total land area (66%), followed by Argentina (23%), Canada (6%), and China (4%). Herbicide-tolerant soybean was the principal GM crop grown in 2002, occupying 62% of the total global genetically engineered crop area, followed by GM corn (21%), GM cotton (12%), and GM canola (5%). During 2002, over 50% of the total global soybean production was GM, which was up from 46% in 2001. Monsanto's Roundup Ready® soybean was grown on 60 million acres (approximately 80% of the total soybean acreage) in the United States in 2002, up from nearly 55 million acres in 2001 (Shoemaker, Johnson, & Golan, 2003). In 2002, over half of the world's human population resided in countries where GM crops were grown. Clearly, the trend in the world—and particularly in the United States—is increased acreage of GM crops, including soybean.

History of Soybean Breeding

It is believed that soybean was first domesticated in the eastern half of north China during the Shang dynasty (ca. 1700–1100 BC; Singh & Hymowitz, 1999). This area is also believed to be the center of origin for soybean. Soybean was likely introduced into North America in 1765 and has been reintroduced many times since this early date. The economic value of soybean in the United States was not realized until the first two decades of the 20th century. Today, soybean is recognized as a world crop, grown largely in the United States, Brazil, Argentina, China, and India for its edible protein and oil. Soybean has major uses in poultry, swine, livestock, pet and human foods, as well as in many industrial and pharmaceutical products.

Soybean is a self-pollinated legume with natural outcrossing of <0.5 to approximately 1% (Carlson & Lersten, 1987). As the result of its self-pollinating reproductive behavior, plant-breeding procedures such as backcrossing, single pod descent, pedigree breeding, and bulk population breeding are some of the more common procedures used to develop improved varieties of soybean (Poehlman & Sleper, 1995). All of these procedures involve making crosses or hybrids by hand pollination followed by selection, testing, and ultimately release of a superior soybean variety.

The development of new improved soybean varieties by the modern soybean breeder is enhanced by using off-season nurseries in the tropics. Many soybean breeders from the private and public sectors use winter nurseries in Puerto Rico, Mexico, Central and South America, and elsewhere to obtain two, three, or more generations in a single season. The use of winter nurseries permits breeders to enter the testing phase earlier; hence, they are able to release new varieties several years earlier than those soybean breeders not using off-season nurseries.

In the early part of the 20^{th} century in the United States, soybean varieties were largely forage types. Early varieties were those introduced from Asia, selections from these introductions, or natural crosses that arose from these introductions. Serious breeding of soybean did not occur until the establishment of the US Regional Soybean Industrial Products Laboratory in 1936 at Urbana, Illinois, in cooperation with other north central state agricultural experiment stations (SAES; Hartwig, 1973).

Early soybean breeding was largely confined to SAES or to the United States Department of Agriculture's Agricultural Research Service (USDA ARS). The passage of the Plant Variety Protection Act (PVP) in 1970 allowed for the intellectual protection of crop varieties, which in turn prompted considerable private industry investment in soybean breeding. In 1980, the US Supreme Court ruled that living matter could be patented (Office of Technology Assessment, 1992). The PVP Act was later modified to conform to the European cultivar protection laws (UPOV). These events stimulated private industry to invest heavily in soybean breeding.

A report by Frey (1996) indicated the following distribution of science person years (SY) for soybean breeding: 45 for SAES, 10 for USDA ARS, and 101 for private industry, for a national total of 156 SY in soybean breeding. As expected, most of the effort in developing improved soybean cultivars (varieties) comes from industry, followed by soybean breeders from SAES (Table 1). The USDA ARS spends the least amount of effort on cultivar development.

Table 1. Science person years devoted to basic plant breeding research (PBR), germplasm enhancement (GE) and cultivar development (CD) by soybean breeders in 1994.

Organization	PBR	GE	CD	Total companies	Total projects
Private industry	8.6	10.9	81.85	101.35	38
USDA ARS	2.3	3.75	3.55	9.6	7
SAES	14.7	11.7	18.6	45.0	25

Note. From Frey, 1996.

Today, the modern soybean breeder has additional tools provided by biotechnology to develop improved soybean varieties. Modern biotechnology in itself will never replace plant-breeding research but rather will enhance and improve upon the efficiency of plant breeding. Scientists in the laboratory can genetically engineer soybean plants with unique genes, but plant breeding is necessary to put the new transgenes via sexual reproduction into the proper genetic background so that it is adapted to the intended areas of use. For example, genetically engineered plants from the laboratory are often poor seed yielders, do not have insect or disease resistance, do not have the proper maturity, and so forth to compete with existing varieties in the marketplace. Seed yield is of paramount importance, because growers cannot profitably grow new varieties aided by biotechnology if they are not competitive in yield to the best varieties already in the marketplace.

According to Frey (1996), there are a number of factors that plant breeders (including soybean breeders) need to consider before using biotechnology to develop new improved varieties. These include: "(a) the need for and utility of genes accessible only from incompatible species; (b) the relative costs of biotechnology and traditional breeding methods for cultivar development; (c) the relative ease whereby plant traits can be manipulated with biotechnology versus traditional breeding methods: (d) the distribution of the benefits of biotechnical inventions; and (e) the acceptance of genetically modified crop cultivars by farmers, society, and regulatory agencies worldwide." Cost is a considerable factor in determining whether to embark on soybean development using biotechnology. Laboratory procedures involving biotechnology can be costly; in addition, regulatory costs can be extreme and time consuming and may be the deciding factor in whether to use the new technology. In addition, at present it is necessary that an efficient soybean transformation system be in place if soybean is to be genetically engineered. Transformation of soybean is becoming more efficient, but still more efficiency is desired (Somers, Samac, & Olhoft, 2003). The last point is of concern to soybean breeders and their employers. A significant number of individuals do not want to consume any food products thought to be derived from GM plant sources. The controversy usually surrounds the consumption of GM cultivars and not biotechnology per se (Frey, 1996). Individuals do not generally object to the tools provided by plant biotechnology, such as tissue culture, marker-assisted selection (MAS), quantitative trait loci (QTLs), chromosomally engineered plants, genomics, and so forth. It remains to be seen if the world's people will openly embrace biotechnologically derived crop plants, including soybean, in the future.

Role of Public Soybean Breeders

The role of the public soybean breeder is in the areas of basic plant breeding research, germplasm enhancement, and varietal development. In addition, most plant breeders in the SAES (and to a more limited extent, USDA ARS soybean breeders who have courtesy SAES appointments) are involved in the education of future plant breeders.

From Table 1, it is obvious that SAES and USDA ARS soybean breeders provide the bulk of the effort in basic plant breeding research. In 1994, 17 SY were devoted to basic plant breeding research, as compared to 8.6 SY from the private sector. Basic plant breeding research involves researching new plant breeding procedures, discovery of new plant breeding methods, comparison of transgenic and nontransgenic soybean, discovery of QTLs associated with economically important traits, development of MAS strategies, comparison of plant breeding procedures, and so forth. The private sector will not exert considerable efforts in many of these areas, because it is long term, often costly research, and it does not immediately lead to the development of new high-yielding improved soybean varieties for the marketplace.

In addition, the public sector soybean breeders conduct most of the research in the area of germplasm enhancement (Table 1). Research in this area includes taking unadapted material (usually plant introductions) and extracting desirable genes for inclusion into highly productive lines. Plant introductions are often black or brown seeded, poor yielding, and generally agronomically inferior to high-yielding released varieties. Traits that have been obtained from plant introductions are many and often include resistance to pests. Obtaining genes from plant introductions and getting them into desirable agronomic types is both time consuming and expensive. Because of the time involved in development of germplasm, private breeders are less likely to be involved in germplasm enhancement because of the profit motive to release new improved varieties quickly. Public breeders often develop these types of materials and then release them as germplasm so that they can be used by public and private breeders as parents for improving existing high-yielding lines.

One of the challenges facing modern soybean breeders is the fact that the germplasm base is extremely narrow (Carter, Gizlice, & Burton 1993; Sneller, 1994). Gizlice, Carter, & Burton (1994) found that only six ancestors constituted more than half of the genetic base of North American soybean germplasm. Because of intellectual property rights, private companies rarely share germplasm for crossing, which narrows the genetic base even further. This poses as a potential threat to soybean improvement in the United States. Perhaps biotechnology as applied by public breeders can help alleviate this potential threat.

Harlan and de Wet (1971) proposed a classification system for plants, based on how easily they could be crossed. They proposed that crop plants could be classified into three gene pools: *primary* (GP-1), *secondary* (GP-2), and *tertiary* (GP-3).

GP-1 consists of biological species; crosses are easily made among plants in this group, resulting in highly fertile progeny. GP-1 was further subdivided into *subspecies A*, which includes cultivated races, and *subspecies B*, which includes spontaneous races. For soybean, this includes cultivated *Glycine max* and its wild progenitor *Glycine soja*.

GP-2 includes all of those species that can cross with those in GP-1, resulting in some fertility in F_1 hybrids. In the case of soybean, there is no GP-2 species, which eliminates the possibility of using GP-2 types of germplasm to improve cultivated soybean (Singh & Hymowitz, 1999).

GP-3 involves the outer limits of potential genetic resources. Hybrids between GP-1 and GP-3 are lethal, anomalous, or sterile, and gene transfer is not possible via sexual hybridization. *Glycine* includes a number of perennial species that are part of GP-3 (Singh &

Hymowitz, 1999). Riggs, Wang, Singh, and Hymowitz (1998) have successfully transferred genes from GP-3 to GP-1 of soybean. Singh and Hymowitz (1999) reported that 16 wild perennial species of the subgenus *Glycine* are present within GP-3 and have not been exploited in plant breeding programs. Perhaps these could be a rich source of genes for soybean improvement, and they should be exploited. It is possible that biotechnology tools could be used to continue to tap the GP-3 source and other unrelated sources of desirable genes to improve upon genetic diversity for soybean improvement.

Biotechnology of soybean, as practiced by public breeders, can be used to improve upon the narrow genetic base available for soybean improvement in the United States. Such methods can include genetic engineering, recombinant DNA technology, cell fusion, and somaclonal variation. This area of research is long term and high risk, and is thus more likely to be conducted by SAES and USDA ARS scientists than by those from the private sector.

Many public breeders, particularly those associated with SAES, are highly involved with educating the next generation of plant breeders. Private breeders rarely contribute directly to this area of involvement. Today, SAES plant breeders are educating future plant breeders with the latest biotechnological advances in molecular genetics/biology and laboratory techniques. This trend is predicted to continue, because modern plant breeders, including soybean breeders, will increasingly use biotechnological tools to develop improved soybean varieties. A good educational program for plant breeders involves educating future plant breeders in the areas of variety development, basic research in plant breeding, principles of germplasm enhancement, and principles of modern molecular biology.

Role of Private Breeders

Approximately 90% of US soybean acres are planted to varieties developed from private programs. Intellectual property protection, the ability to earn a good return on research investment, and reductions in public budgets have shifted the majority of the soybean breeding effort from the public to the private sector.

The use of biotechnology in private breeding programs is dominated by large companies with the financial resources, facilities, equipment, and personnel to conduct high-risk research in finding genes and transforming soybeans with useful traits. Financial rewards from insertion of traits (such as tolerance to Roundup herbicide developed and patented by Monsanto Corporation) are tremendous. In addition to the millions of gallons of Roundup that are marketed, Monsanto receives a technology fee of $8.00 for most of the 50 million units of soybean seed that is sold—not to speak of the fees received for biotechnology traits inserted into other crops such as cotton and corn.

Other large corporations, such as Syngenta and Dupont-Pioneer, in addition to Monsanto, are very involved in the development of new traits via biotechnology as well as DNA-marker-assisted breeding. They use marker-assisted selection to screen for resistance to soybean cyst nematode, brown stem rot, and phytophthora root rot. Marker-assisted selection is reducing research costs by allowing the selection of specific traits from large germplasm pools in much shorter time than that required by conventional techniques. Because fewer resources are being used, profit potential is increased. Marker-assisted selection is primarily being used in earlier breeding generations to solely advance strains with the desired traits for future testing. This ensures that subsequent field evaluations, which are costly, will involve strains with traits that have the highest probability of becoming a profitable product. Soybean breeding programs with access to DNA marker technology will have a greatly enlarged tool kit for an enhanced probability of success in cultivar development. It is likely that smaller programs or companies without this technology will be at a disadvantage and may not be able to compete in the future to improve their position in the marketplace. To circumvent this problem, small soybean breeding programs without access to biotechnology have occasionally formed alliances with universities or other companies who can help them keep pace with larger programs in a very competitive business.

Joint Private/Public Research Efforts in Breeding

Biotechnology offers greater opportunities for joint private/public efforts in soybean improvement. Using biotechnology to develop soybean varieties is often complex, laborious, and expensive. In many instances, no one company or institution will have all of the biotechnology pieces to the puzzle, which means that there needs to be cooperation between public and private soybean breeders. As reported by Frey (2000), little formal interaction occurred between public and private breeding sectors for most crops from 1960 to 1985. However, it is now more common for breeders from industry and the public sector to interact at symposia and other professional meetings. A good example of this is that public and private soybean breeders gather once each year to exchange information at the Soybean Breeder's Workshop. This has been a highly successful venue for dialogue between the private and public sectors. In addition, there are more contributions from industry to support graduate education. As biotechnological developments continue, breeders from both sectors need enhanced cooperation to maximize soybean improvement through breeding.

Funding for graduate students has become more of a challenge in recent times. Frey (2000) reported that from 1980 to the mid-1990s, approximately 6% of the plant breeding positions from the public sector involved in graduate education were eliminated. Clearly, if we are to provide highly educated soybean breeders for the future, this trend needs to be changed. Industry does provide funds for graduate education in many instances, but more assistance from industry in this area would be desirable. Graduate stipends are becoming increasingly competitive today as the best institutions compete for the best students; if the best minds are going to be attracted to the field of plant breeding, stipends need to be funded accordingly.

Conclusions

The first-generation traits to be put into soybean varieties via biotechnology were herbicide resistance with glyphosate resistance being the most prevalent. More new herbicide-resistant soybeans are likely in the future, as life science companies continue to search for additional herbicides and genetic resistance to them. The primary outcome of the first-generation traits—herbicide resistant soybean varieties—has been reduced costs and increased production efficiency.

At present, we are witnessing the second generation of traits put into soybean via biotechnology—for example, high-oleic fatty acid content through particle-bombardment-mediated transformation (Kinney, 1996). Another example of a so-called second-generation trait is the development of high-lysine soybean (Falco et al., 1995). Soybean has also been transformed with Bt technology for resistance to lepidopteran pests (Walker, Boerma, All, & Parrott, 2002). Additional traits that are not necessarily related to improving production efficiency are likely.

Third-generation soybean lines from biotechnology are difficult to predict, because much of the research conducted is not yet reported, and scientists are not always willing to discuss where they are headed because of intellectual property protection and competitive issues. One might surmise, however, that soybean biotechnology will likely be involved in areas such as using soybean as factories to produce specialty chemicals. Products in this area could include production of special enzymes, long-chain fatty acids, vitamins, pharmaceuticals, drought and cold tolerance, bioplastics, increased yield, and many other benefits. Biotechnology opens up many possibilities for the future that are both foreseen and unforeseen. Biotechnology promises to continue to revolutionize soybean breeding.

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